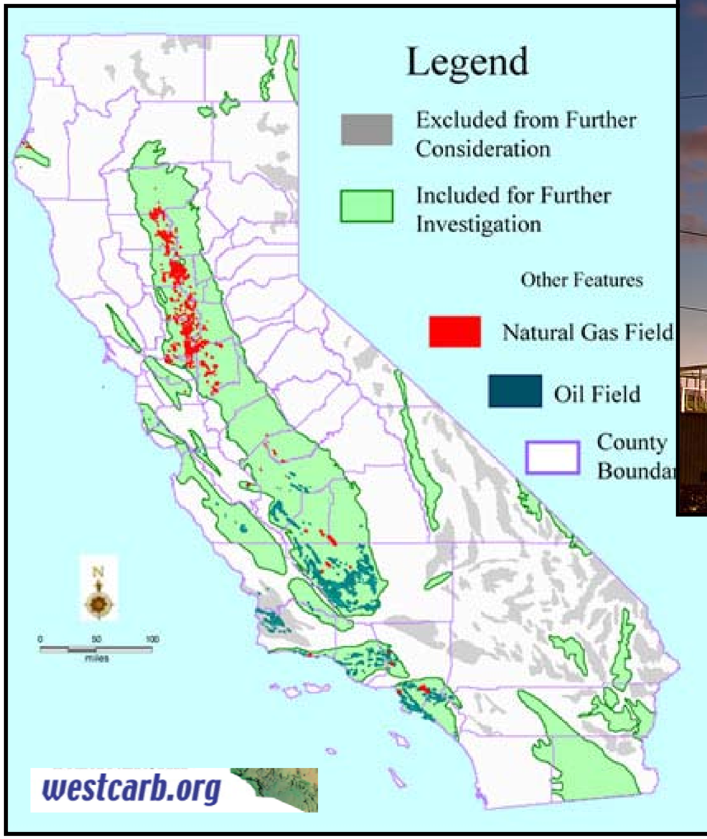
Reducing Emissions in California Through Carbon Capture and Sequestration



S. Julio Friedmann

Carbon Management Program APL
Global Security Principle Directorate, LLNL
friedmann2@llnl.gov
http://co2.llnl.gov/

Conclusions

Current knowledge strongly supports carbon sequestration as a successful technology to dramatically reduce CO_2 emissions.

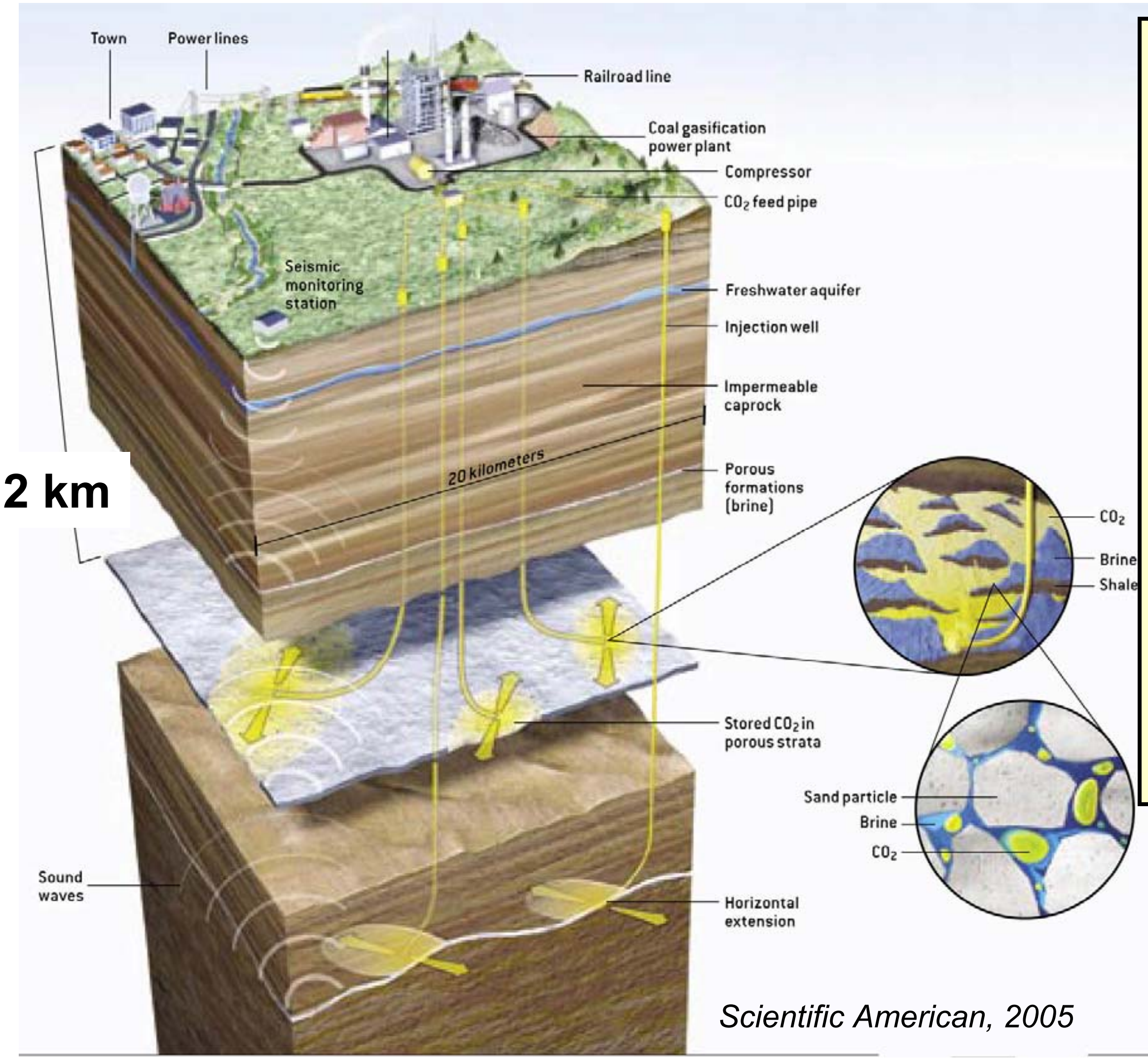
Current science and technology gaps appear resolvable at scale

Site characterization, monitoring, and hazard assessment & management are keys to safe and successful deployment

California's specific mix of carbon sources and geology provide real, near term opportunities to dramatically reduce emissions with CCS

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

Geological carbon sequestration is the deep injection of CO_2 to avoid atmospheric release

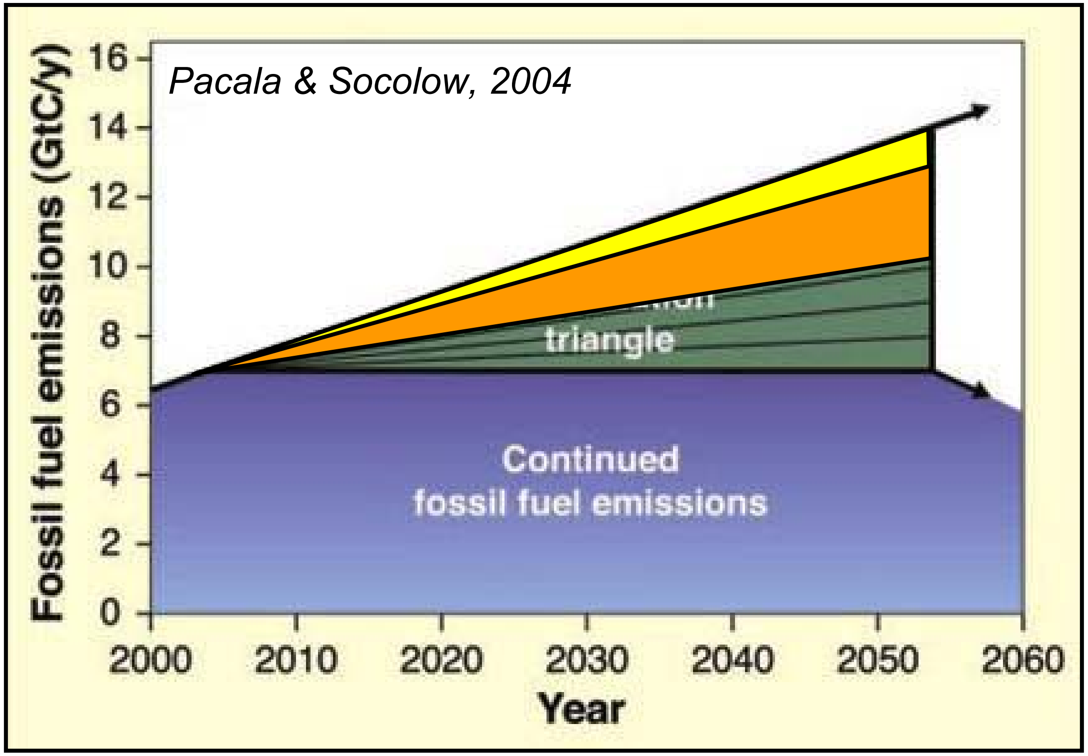


Scientific American, 2005

CO_2 can be stored in deep geological formations as a pore-filling fluid:

- **Saline Formations:**
  largest capacity (>2200 Gt)
- **Depleted Oil & Gas**
  potential for enhanced oil and natural gas recovery

CO_2 Capture & Sequestration (CCS) can provide 15-50% of global GHG reductions

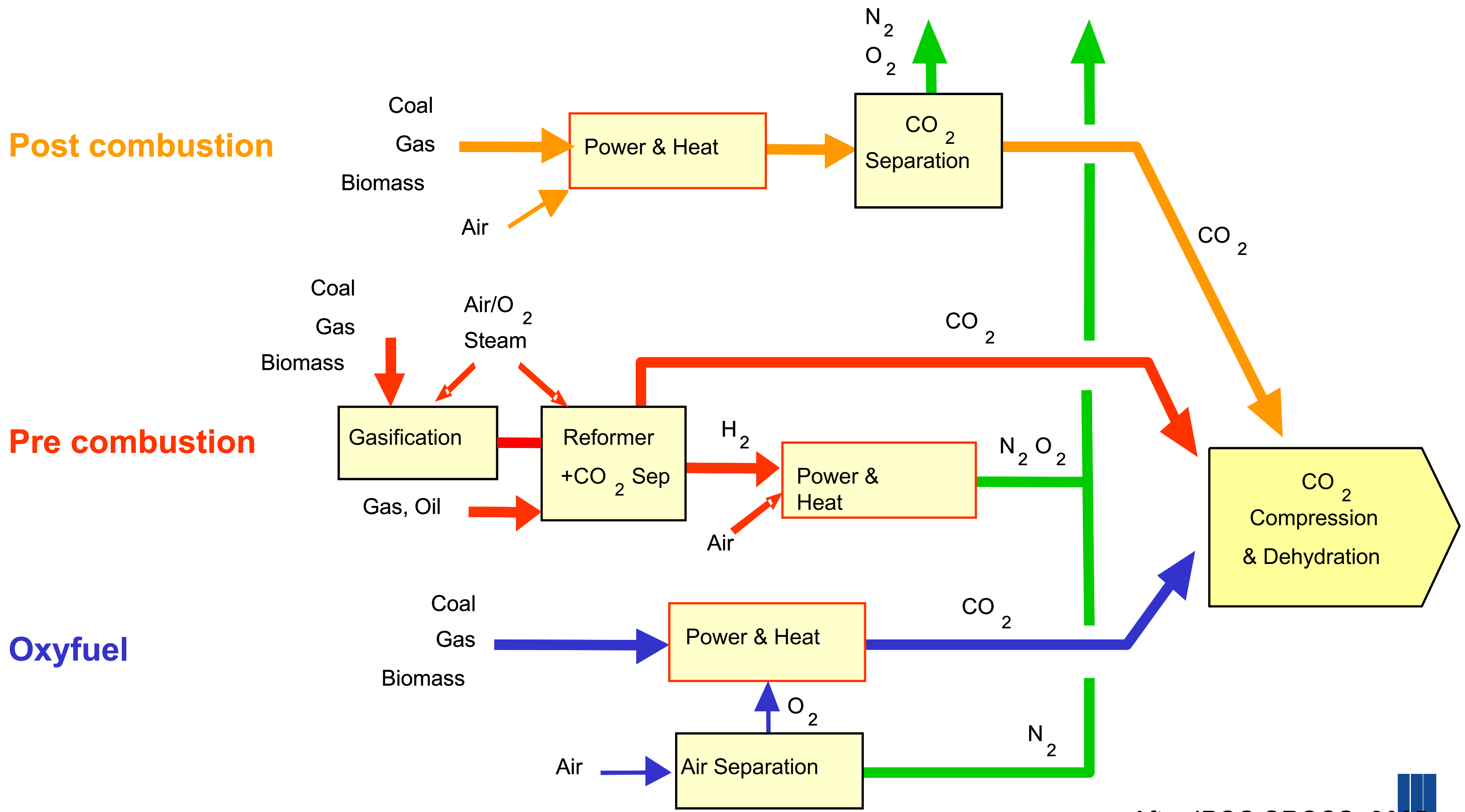


- ***ACTIONABLE***
- ***SCALEABLE***
- ***COST-EFFECTIVE***

- **A key portfolio component (w/ cons., effic., nuclear, renew.)**
- **Cost competitive to other carbon-free options (enables others, like hydrogen)**
- **Uses proven technology**
- **Applies to existing and new plants**
- **Room for cost reductions (50-80%)**

High purity (>95%) CO_2 streams are required for storage

Three technology pathways can capture and separate large volumes of CO_2



After IPCC SRCCS, 2005

High purity (>95%) CO_2 streams are required for storage

Capture devices for standard existing plants are relatively high in cost.

At present, all three approaches to carbon capture and separation appear equally viable

Typical PC plant	\$40-60/t CO_2
Typical gasified plant	\$30-45/t CO_2
Oxyfired combustion	\$40-60/t CO_2*
Low-cost opportunities	\$ 5-10/t CO_2

Refineries, fertilizer & ethanol plants, polygeneration, cement plants, and gas processing facilities are cheapest. Pursuit of coal-to-liquids, H_2 fuel production, and oil shales will make additional high concentration streams

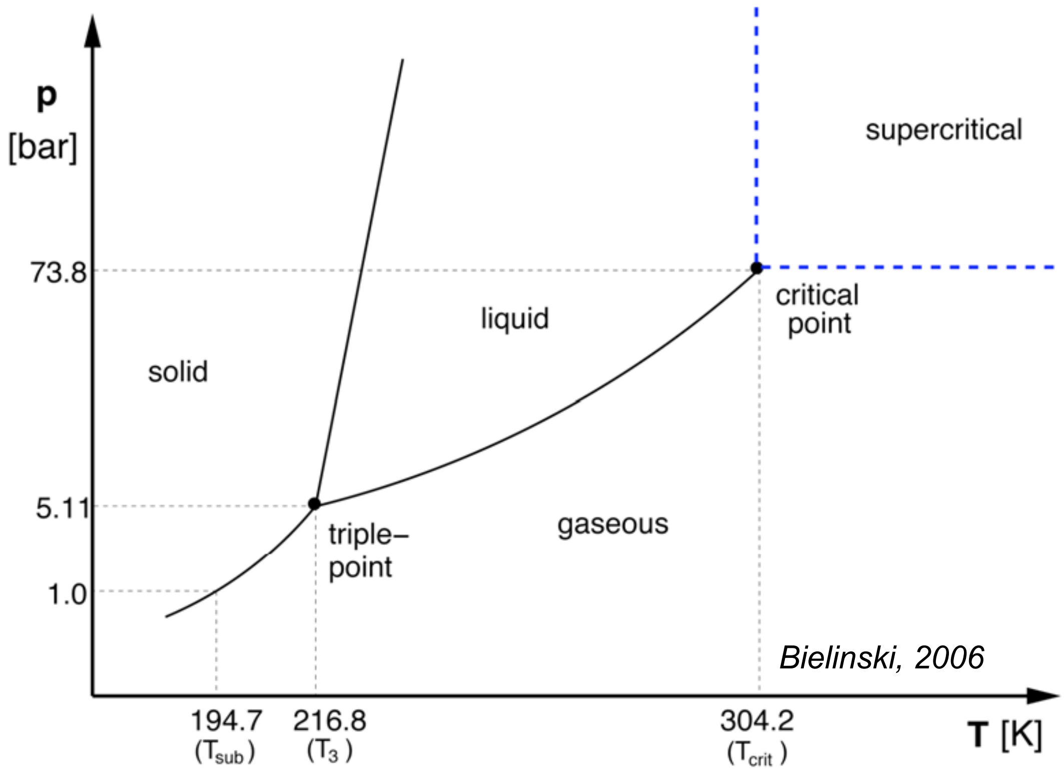
** Not yet ready for prime time*

What empirical evidence is there that transport & geological storage of CO_2 can be done safely?

- Nature has stored oil and natural gas in underground formations over geologic timeframes, i.e. millions of years
- Gas and pipeline companies are today storing natural gas in underground formations (>10,000 facility-years experience)
- Naturally occurring CO_2 reservoirs have stored CO_2-rich gas underground for millions of year, including large volumes in the US (WY, CO, TX, UT, NM, MS, WV)
- Almost 3,000 miles of CO_2 pipelines are operate in N. America, carrying over 30 million tons of CO_2 annually
- Well over 100 million tons of CO_2 have already been injected into oil reservoirs for EOR as well as into deep saline aquifers (over 80 projects have been implemented worldwide)
- Three commercial sequestration projects have demonstrably sequestered CO2 at injection rates ~ 1 million t CO_2/y for years across a wide range of geological settings

Geologic CO_2 Sequestration Targets & Storage Mechanisms

Physical properties of supercritical CO_2



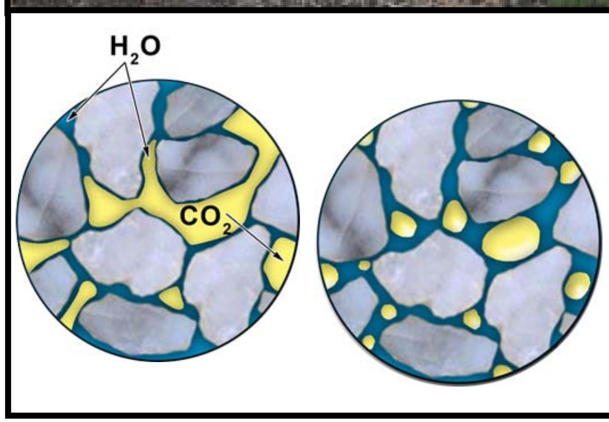
Commercial CO_2 sequestration will proceed only in those geological settings where CO_2 will be in a supercritical state.

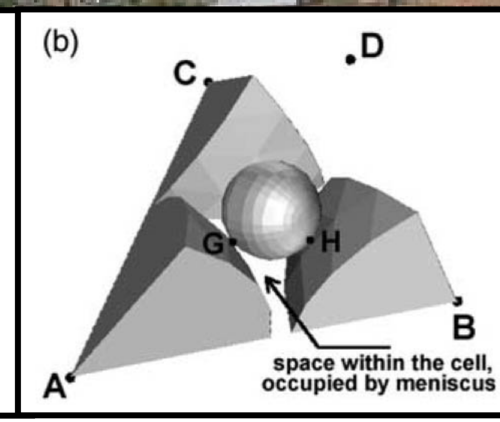
This means it will have a density like oil and viscosity less than oil but much more than methane.

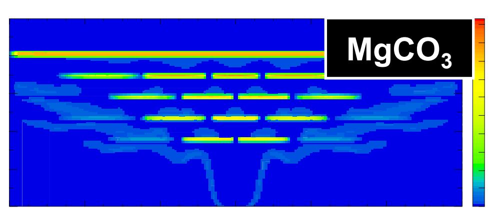
CO_2 property	Likely minimum T (35°C) and P (8 MPa)	Likely maximum T (80°C) and P (40 MPa)
Density: kg/m^3	419	823
Viscosity: mPa/s	0.030	0.076

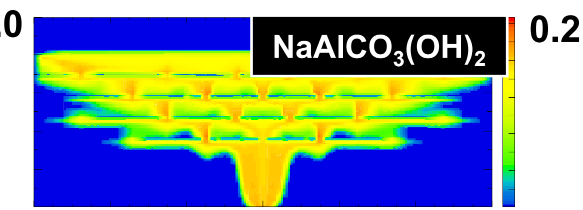
NIST chemistry webbook, 2006

Storage mechanisms are sufficiently well understood to be confident of effectiveness









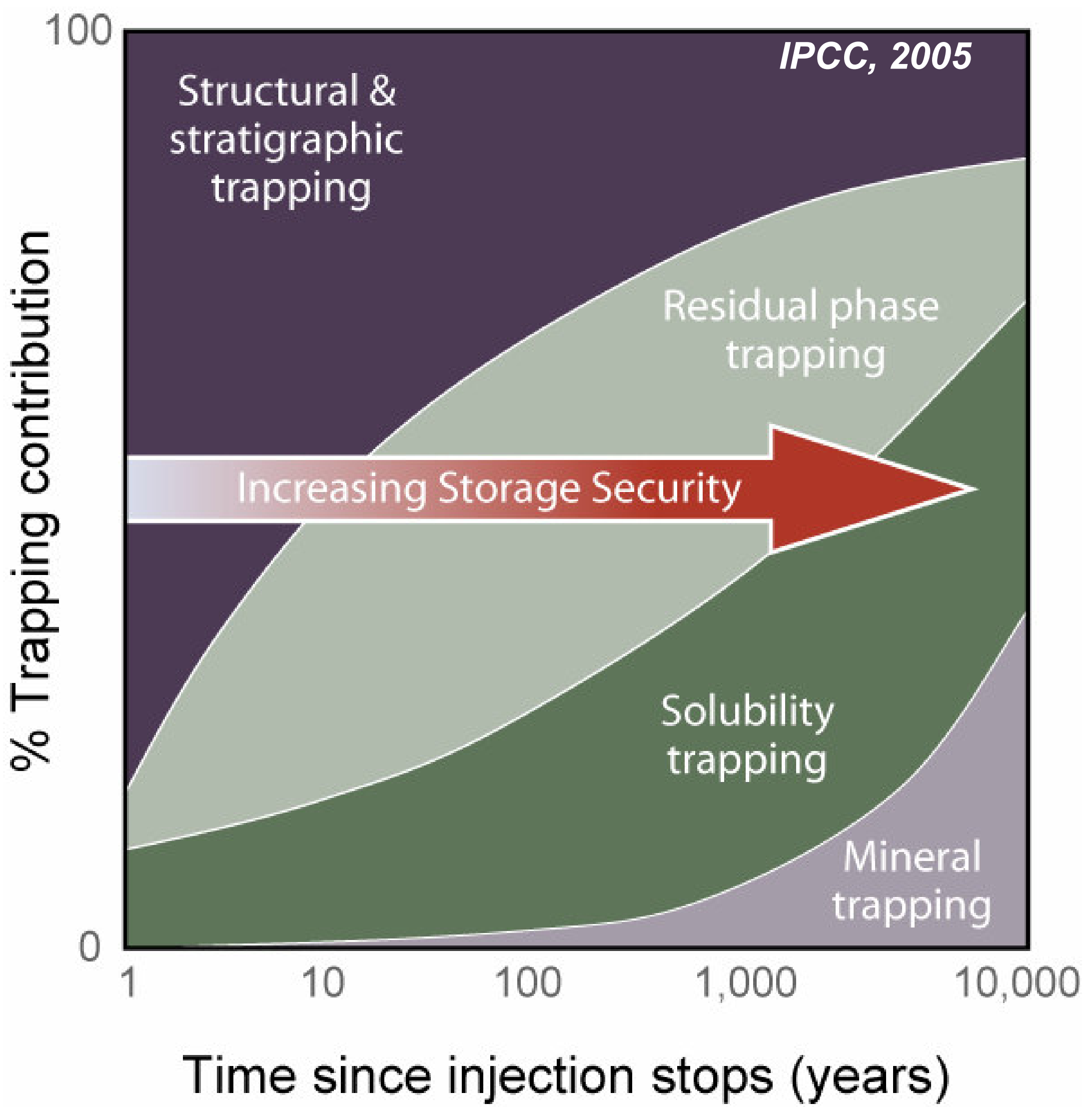
Physical trapping
- Impermeable cap rock
- Either geometric or hydrodynamic stability

Residual phase trapping
- Capillary forces immobilized fluids
- Sensitive to pore geometry (<25% pore vol.)

Solution/Mineral Trapping
- Slow kinetics
- High permanence

Gas adsorption
- For organic minerals only (coals, oil shales)

The crust is well configured to trap large CO_2 volumes indefinitely

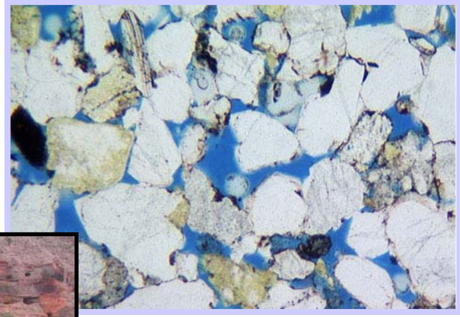


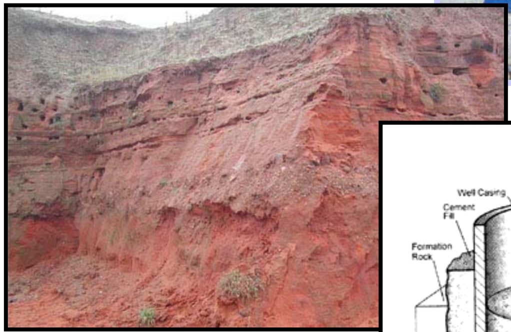
Multiple storage mechanisms working at multiple length and time scales should trap free-phase CO_2 plumes,

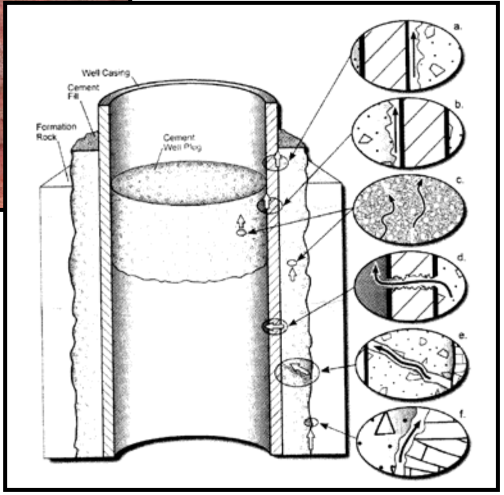
This means that over time risk decreases and permanence increases

A successful GCS site requires ICE

Injectivity *Capacity* *Effectiveness*







Gasda et. al, 2005

Injectivity
- Rate of volume injection
- Must be sustainable (years)

Capacity
- Bulk (integrated) property
- Total volume estimate
- Sensitive to process

Effectiveness
- Ability for a site to store CO_2
- Long beyond the lifetime of the project
- Most difficult to define or defend

Conventional technology is sufficient to determine ICE for a site

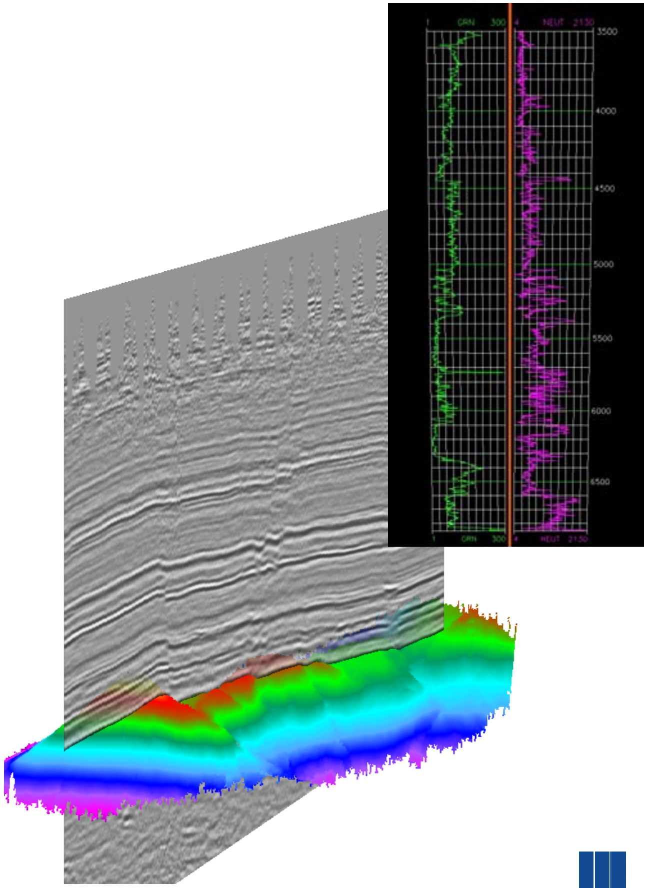
Site selection should require due diligence in characterization & validation

Injectivity
Capacity
Effectiveness

Ideally, project site selection and certification would involve detailed characterization. In most cases, this will require new geological and geophysical data sets.

For Depleted Oil & Gas Fields:
- Injectivity & capacity well established
- Objective measures of effectiveness exist

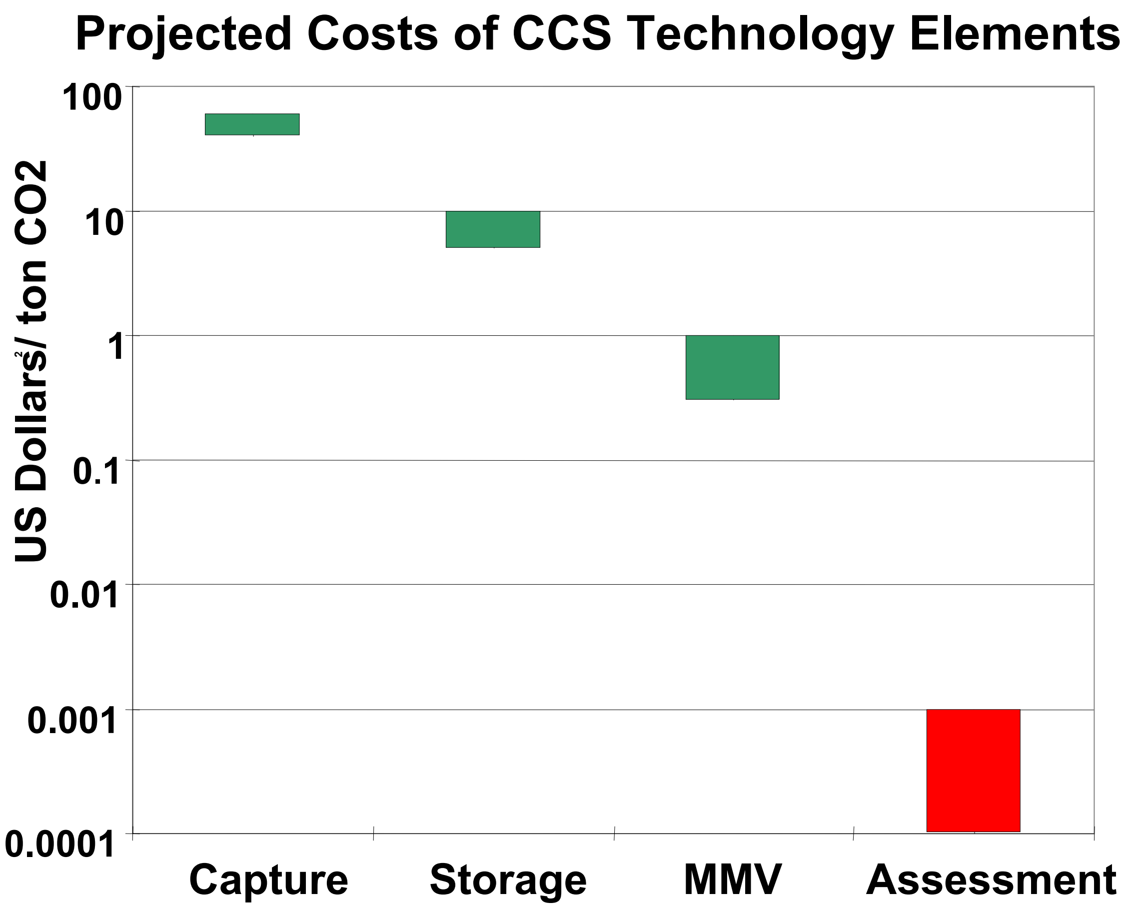
For Saline Aquifers:
- ICE could be estimated; would probably require exploratory wells and 3D seismic
- Include cores, followed by lab work



Variability in site geology, geography, and regulations demands flexibility in site permits requirements

Assessments represent the lowest cost, highest impact step in CCS

For any large injection volume, local assessment is extremely low in cost and can be executed with conventional technology



Friedmann et al., in press

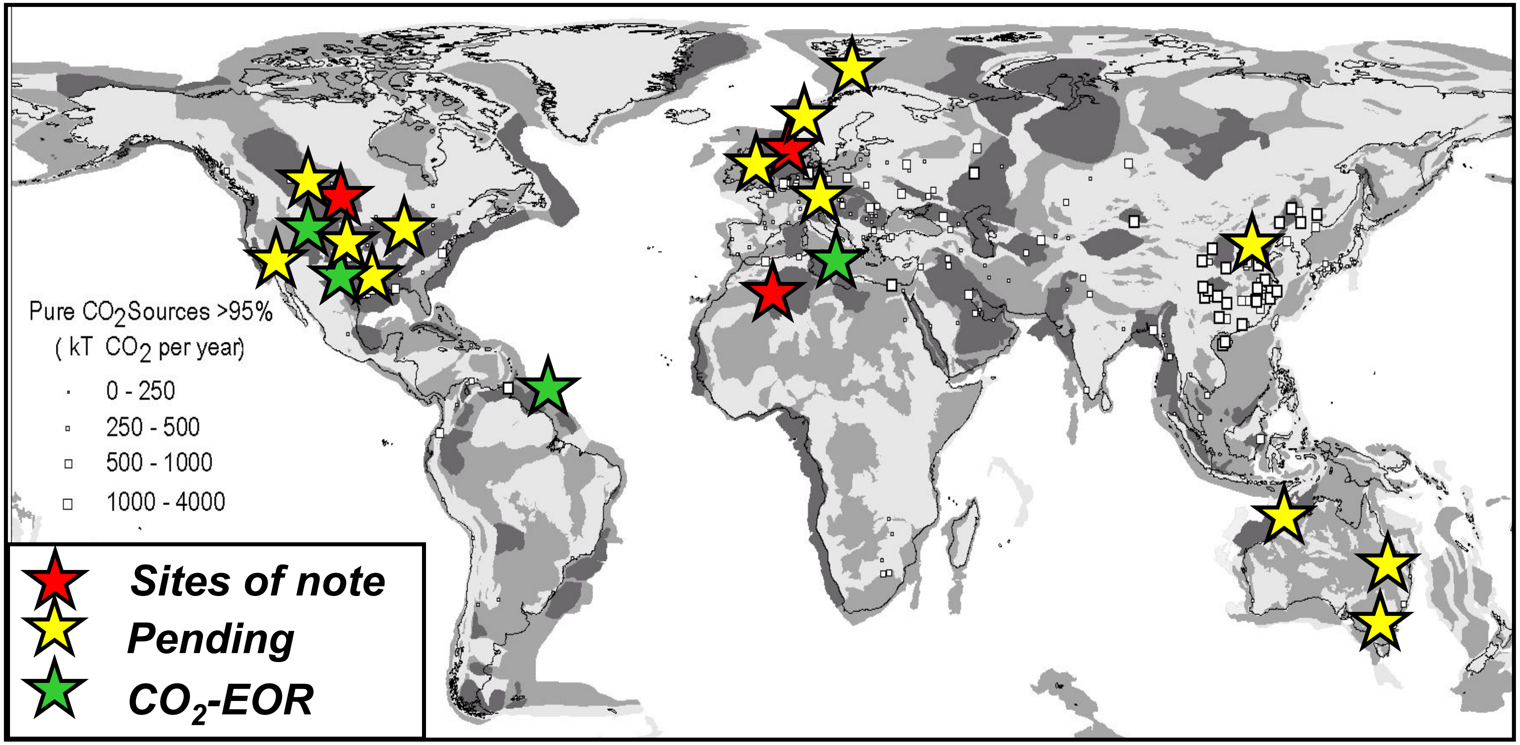
On a national level, assessments should proceed through geological surveys or in partnerships with the oil and gas industry

Site assessments may be paid for by the site operator, the CO_2 owner, or through bonds.

This step is vital, and should be supported fully.

Several large projects exist, with many pending

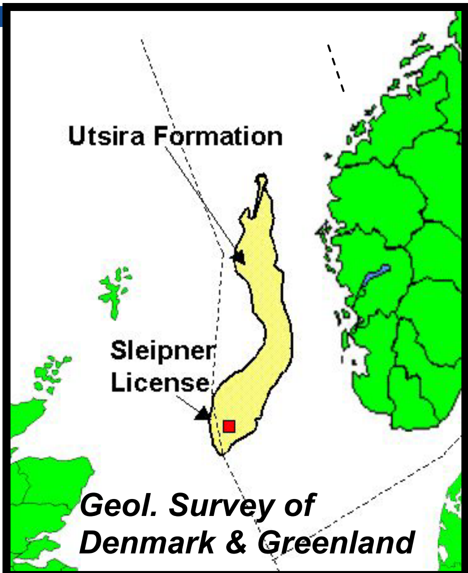
The projects, especially the three commercial sequestration projects, demonstrate the high chance of success for CCS



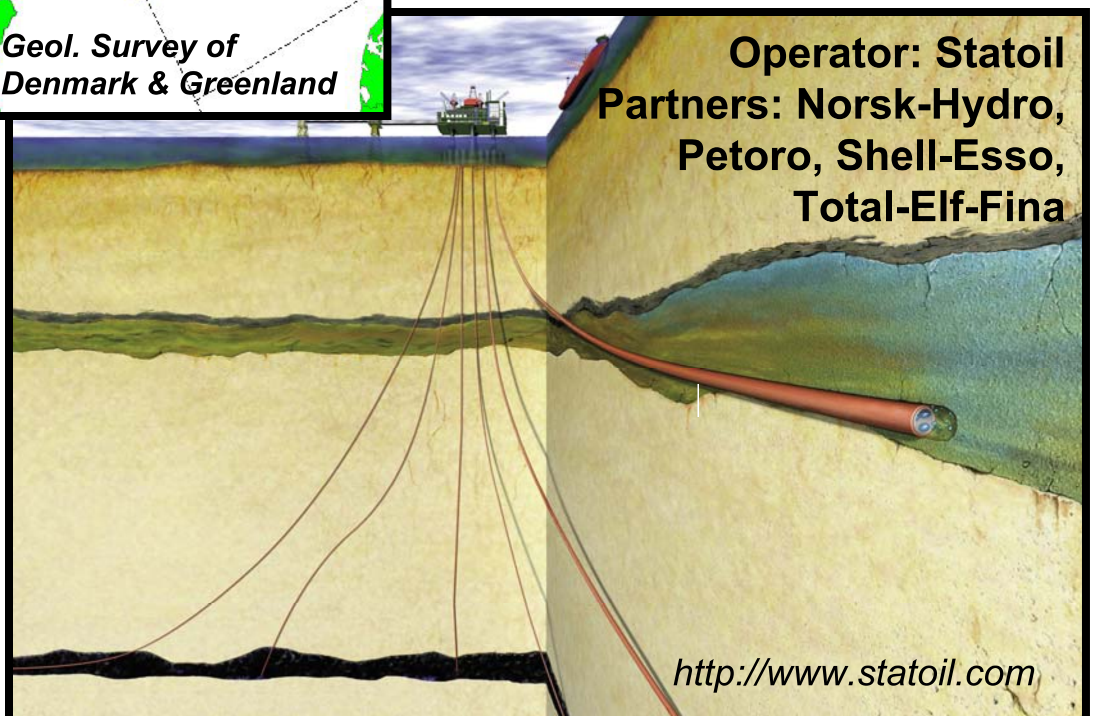
These studies are still not sufficient to provide answers to all key technical questions or to create a regulatory structure

Sleipner Vest project demonstrates 1st order viability of commercial storage

FIRST major attempt an large volume CO_2 sequestration, offshore Norway. Active since 1996. Monoethanolamine (MEA) capture



Economic driver: Norwegian carbon tax on industry ($50/ton C)
Cost of storage: $15/ton C

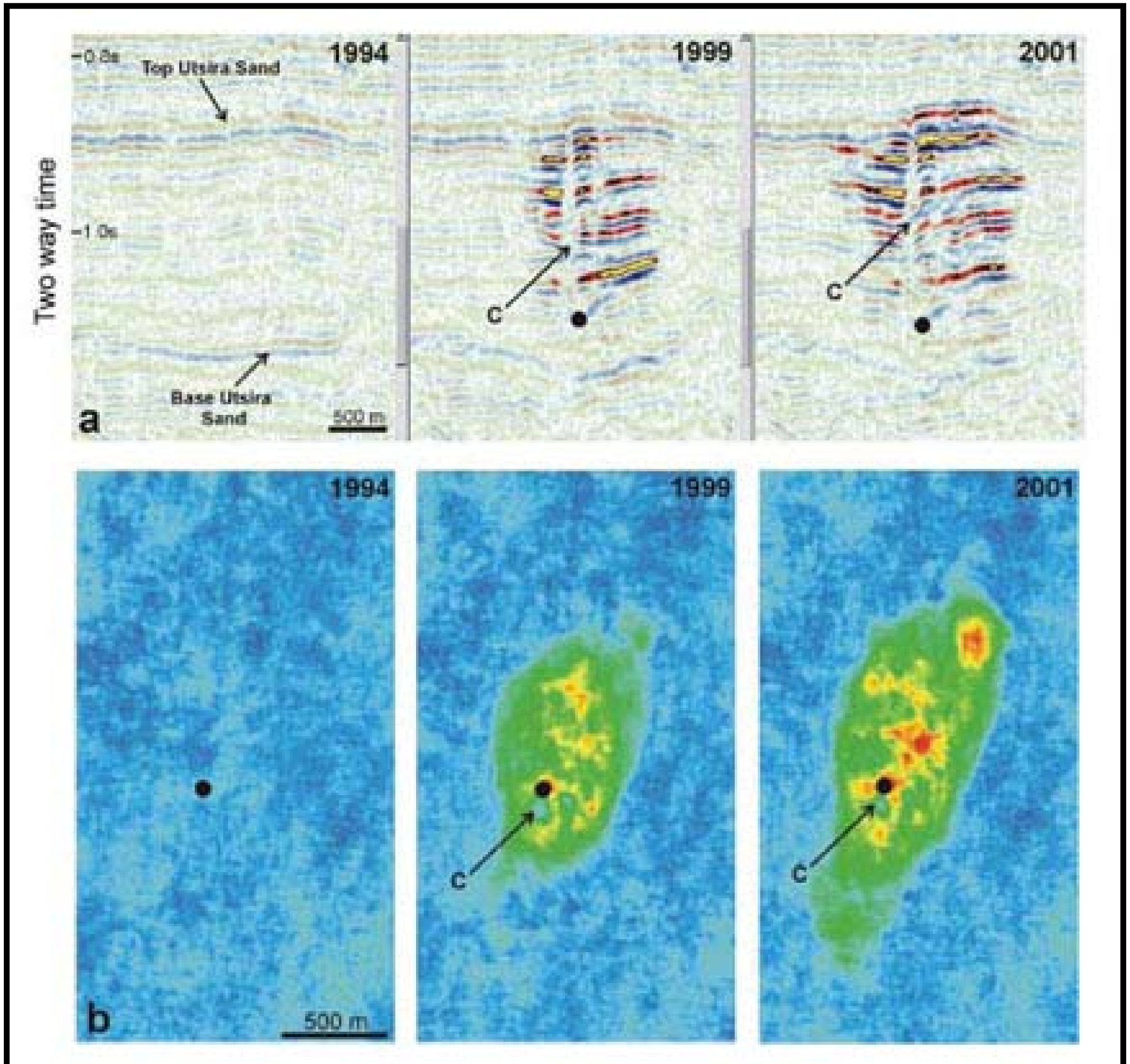


Target: 1 MM t CO_2/yr. So far, 11 MM t

Miocene Aquifer: DW fan complex

- 30-40% porosity, 200 m thick
- high perm. (~3000 mD)
- between 15-36 °C – w/i critical range

Sleipner monitoring supports the interpretation that CO_2 can be imaged and has not escaped



Chadwick et al., 2004

This survey has sufficient resolution to image 10,000 t CO_2, if collected locally as a free-phase.

The CO_2 created impedance contrasts that revealed thin shale baffles within the reservoir.

Weyburn: Transport from North Dakota gasification plant to EOR field

CO_2 Delivery

- 200 miles of pipe
- Inlet pressure 2500 psi; delivery pressure 2200 psi
- 5,000 + metric tonnes per day
- Deliver to Weyburn and now Midale

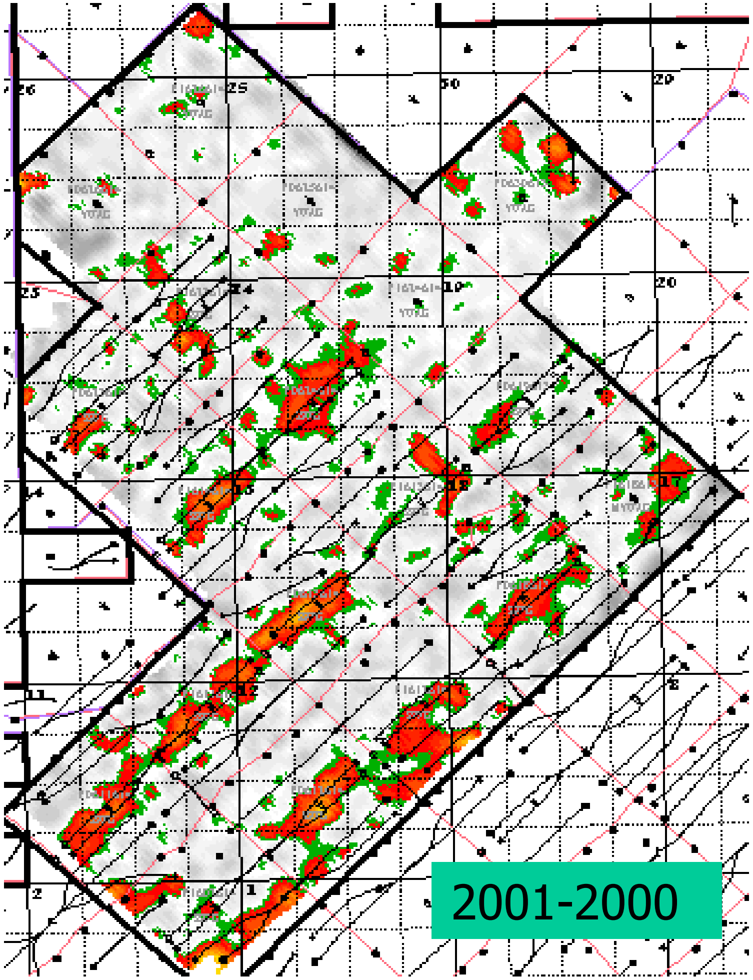
Weyburn field

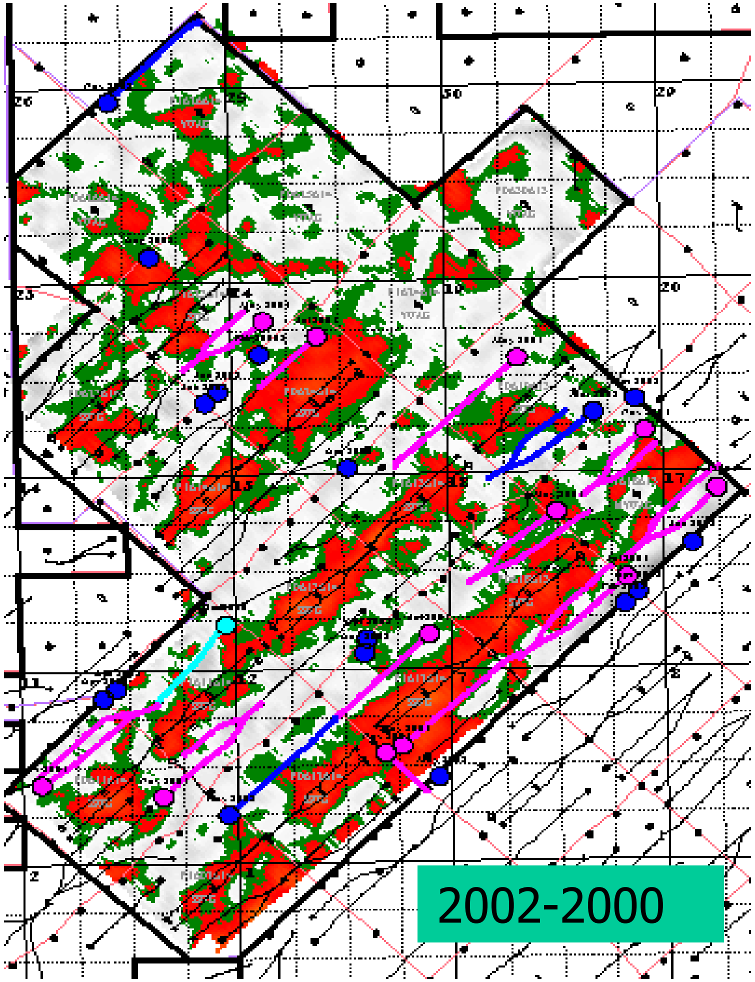
- Discovered: 1954
- >2.0 Gbbl OOIP
- Additional recovery ~130 MM barrels
- >26 M tons CO2 stored
- 4 year, $24M science project; expand to second phase

Courtesy PTRC

Time-lapse seismic surveys show changes in CO_2 saturation near wells: no leakage

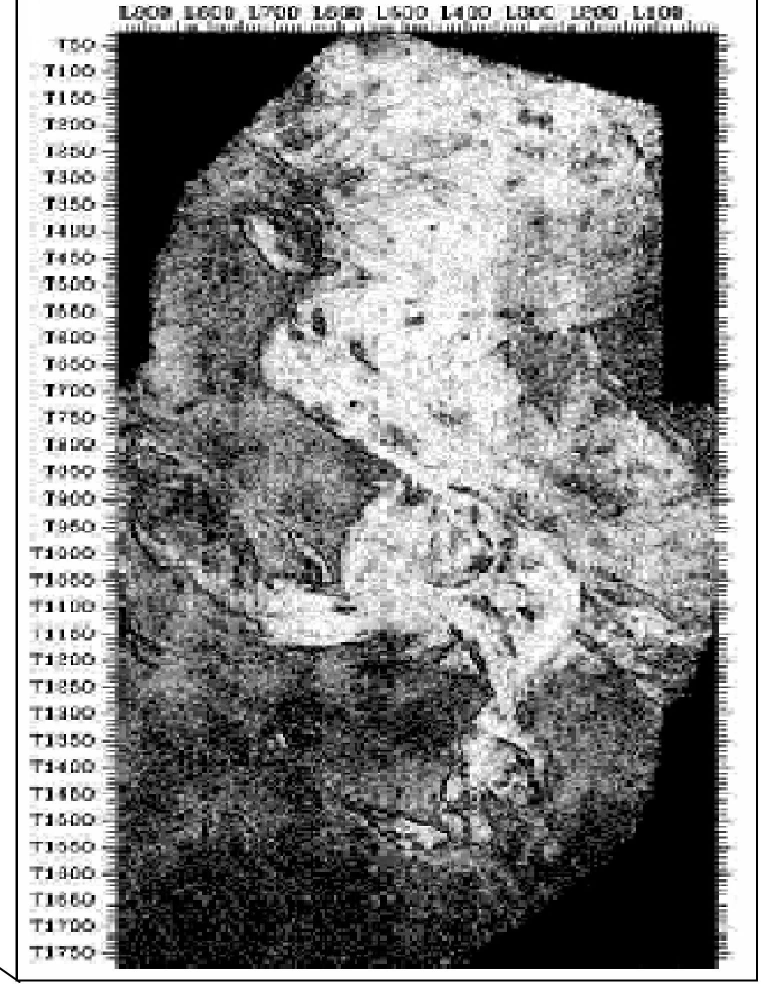
Marly Zone





Wilson & Monea 2004

In Salah (Algeria) CO_2 storage project

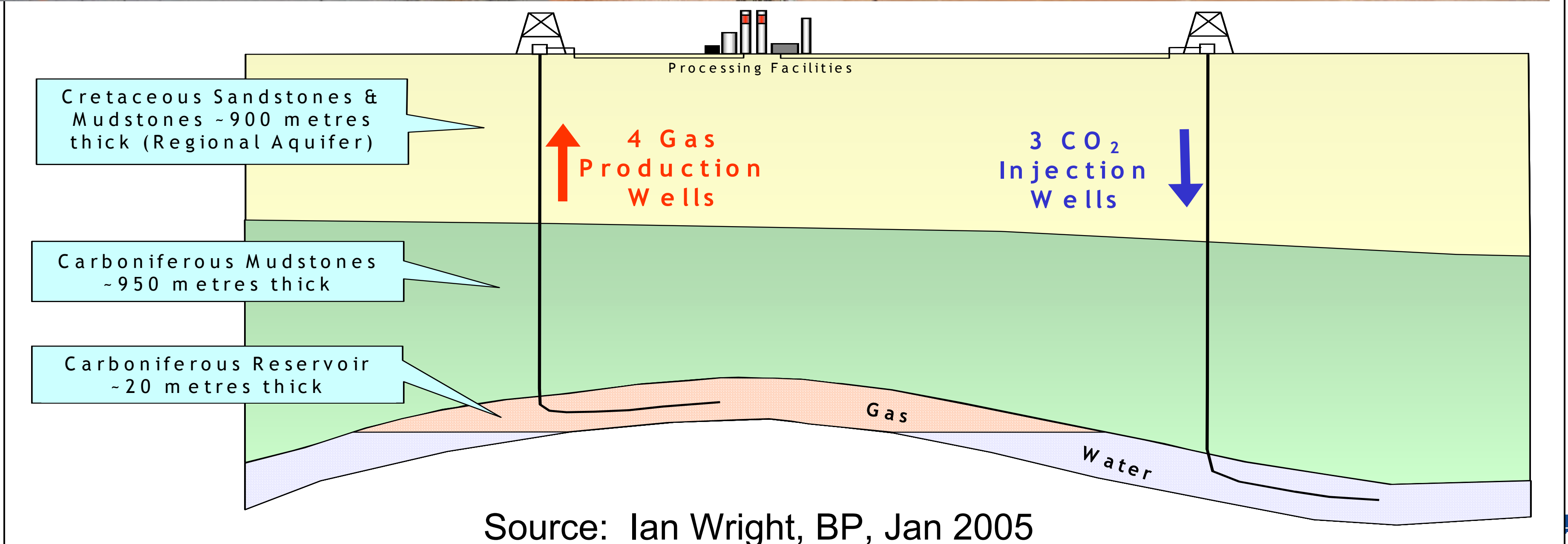


In Salah Project, Kretchba field

Rittiford et al., 2004

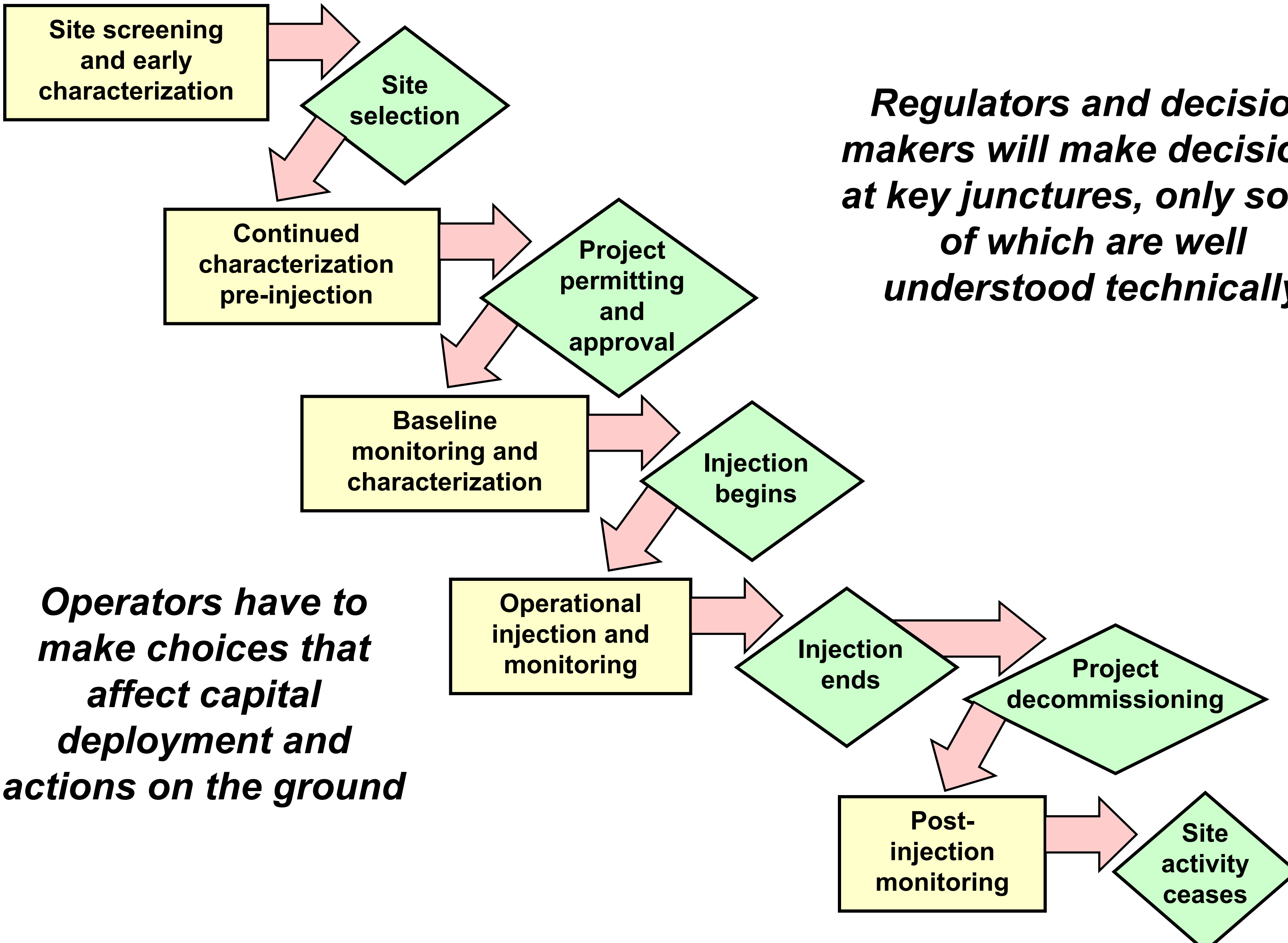
1 M t/yr CO_2 separated from produced gas being injected into aquifer below gas zones.

1 M t/yr CO_2 separated from produced gas is injected into deep saline aquifer below gas zones



Source: Ian Wright, BP, Jan 2005

Deployment efforts have brought focus to CCS operations life-cycle and its key issues

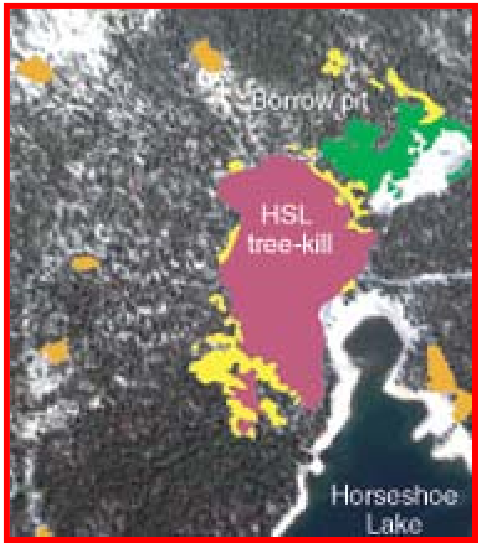


Regulators and decision makers will make decisions at key junctures, only some of which are well understood technically

Operators have to make choices that affect capital deployment and actions on the ground

Leakage risks remain a primary concern

1) High CO_2 concentrations (>15,000 ppm) can harm environment & human health.
2) There are other potential risks to groundwater, environment
3) Concern about the effectiveness & potential impact of widespread CO_2 injection
4) Economic risks flow from uncertainty in subsurface, liability, and regulations

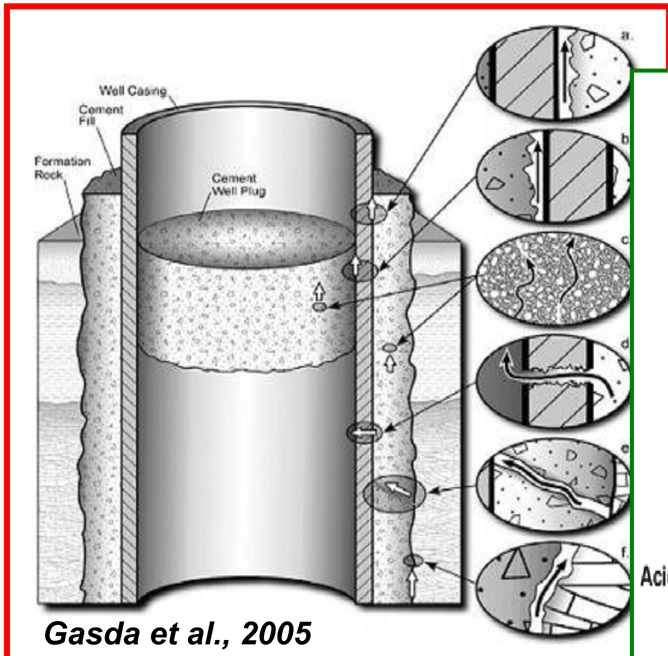


Elements of risk can be prioritized

- Understanding high-permeability conduits (wells and faults)
- Predicting high-impact effects (asphyxiation, water poisoning)
- Characterizing improbable, high-impact events (potential catastrophic cases)

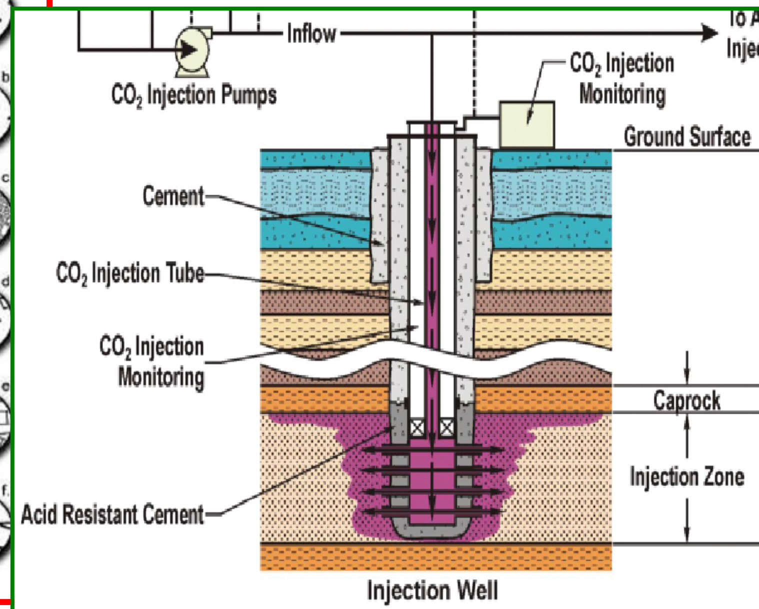
Wells represent the main hazard to GCS site integrity

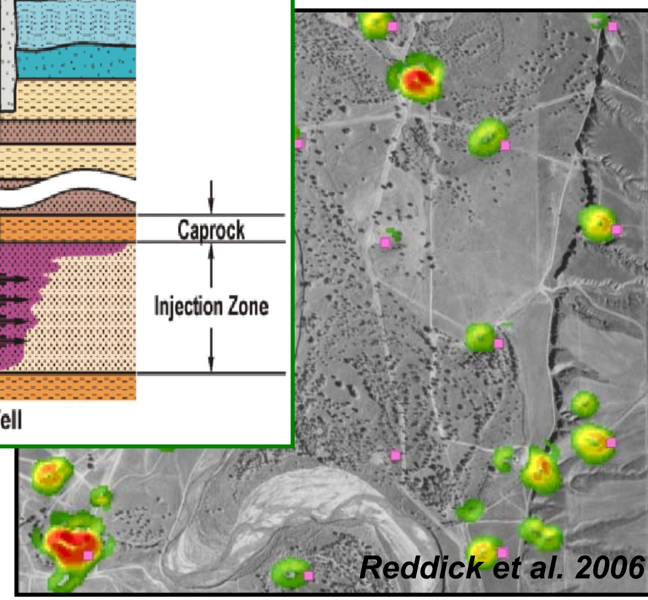
We have some understanding of well failure modes



Gasda et al., 2005

We can properly design CO_2 wells and plug failed wells





Reddick et al. 2006

We can identify and recomplete lost wells

Managing and maintaining well integrity is important to avoiding failure and risk minimization

Crystal Geyser, UT represents an analog for well leakage, fault leakage, & soil leakage

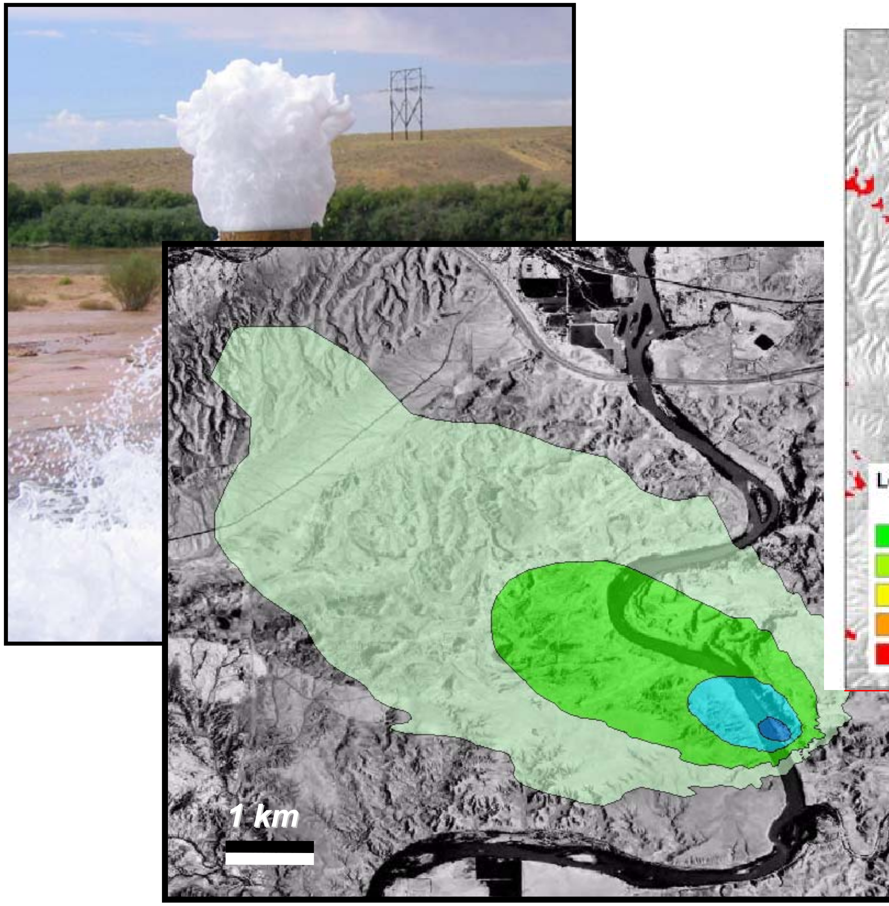
Drilled in 1936 to 801-m depth initiated CO_2 geysering.

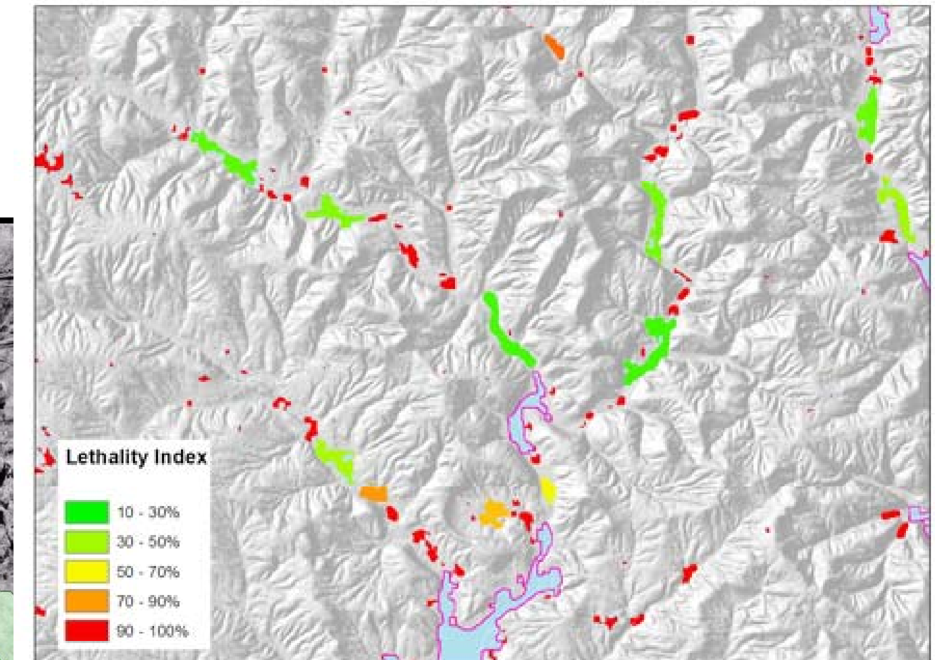
CO_2 flows from Aztec sandstone (high P&P saline aquifer)

Oct. 2004, LLNL collected flux data

- Temperature data
- Meteorological data
  - Low wind (<2 m/s)
- 5 eruptions over 48 hrs
- Four eruptions and one pre-eruption event sampled

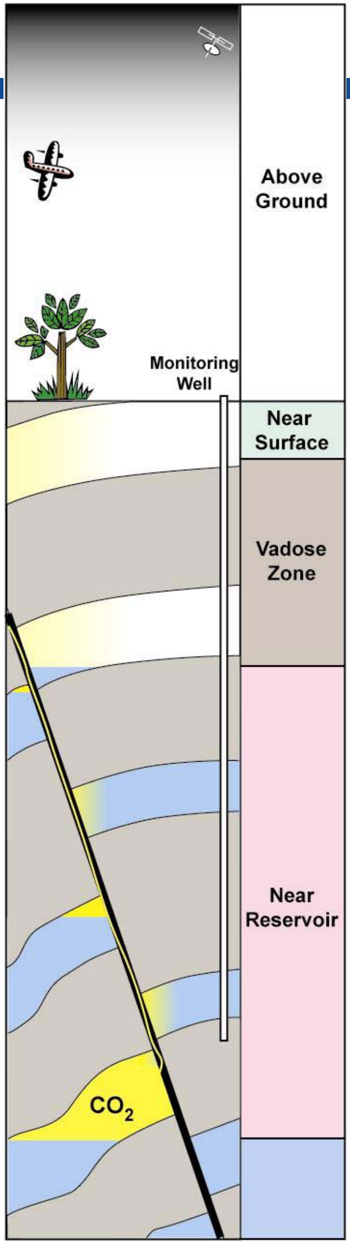
The risks of leakage appear to be both small and manageable





Wells present a challenge to integrity and monitoring which could be resolved through technology application & regulation

Monitoring and verification (M&V) is likely to be required



MMV serves these key roles:

- Understand key features, effects, & processes
- Injection management
- Delineate and identify leakage risk and leakage
- Provide early warnings of failure
- Verify storage for accounting and crediting

Currently, there are abundant viable tools and methods; however, only a handful of parameters are key

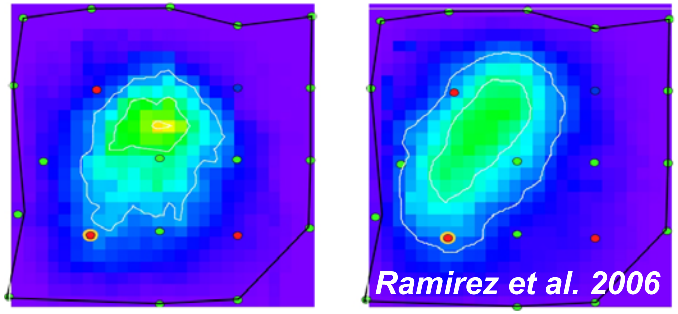
- Direct fluid sampling via monitoring wells (e.g., U-tube)
- T, P, pH at all wells (e.g., Bragg fiber optic grating)
- CO_2 distribution in space: various proxy measures
  (Time-lapse seismic clear best in most cases)
- CO_2 saturation (ERT, EMIT likely best)
- Surface CO_2 changes, direct or proxy
  (atmospheric eddy towers best direct; LIDAR may surpass)
  (perfluorocarbon tracing or noble gas tracing best proxies)
- Stress changes (tri-axial tensiometers)

Many tools exist to monitor and verify CO_2 plumes and have been tested

Parameter	Best tool	Other tools
Fluid composition	Direct sample	(Advanced simulation)
T, P fieldwide	Thermocouples & pres. sensors	Fiberoptic Bragg grating
Subsurface pH monitoring	pH sensors	
CO_2 distribution	Time-lapse seismic	(microseismic, tilt, VSP, electrical methods)
CO_2 saturation	Electrical methods (ERT)	(advanced seismic)
Surface detection	Soil gas, PFC tracing	(Atmos. eddy towers, FTIRS, LIDAR, hyperspectral)
Stress/strain changes	(Tri-axial tensiometers)	Bragg grating, tilt, InSAR

~4600 m^3 of CO_2 injected

~6300 m^3 of CO_2 injected



The Western Region is at the center of national action and interest in carbon management

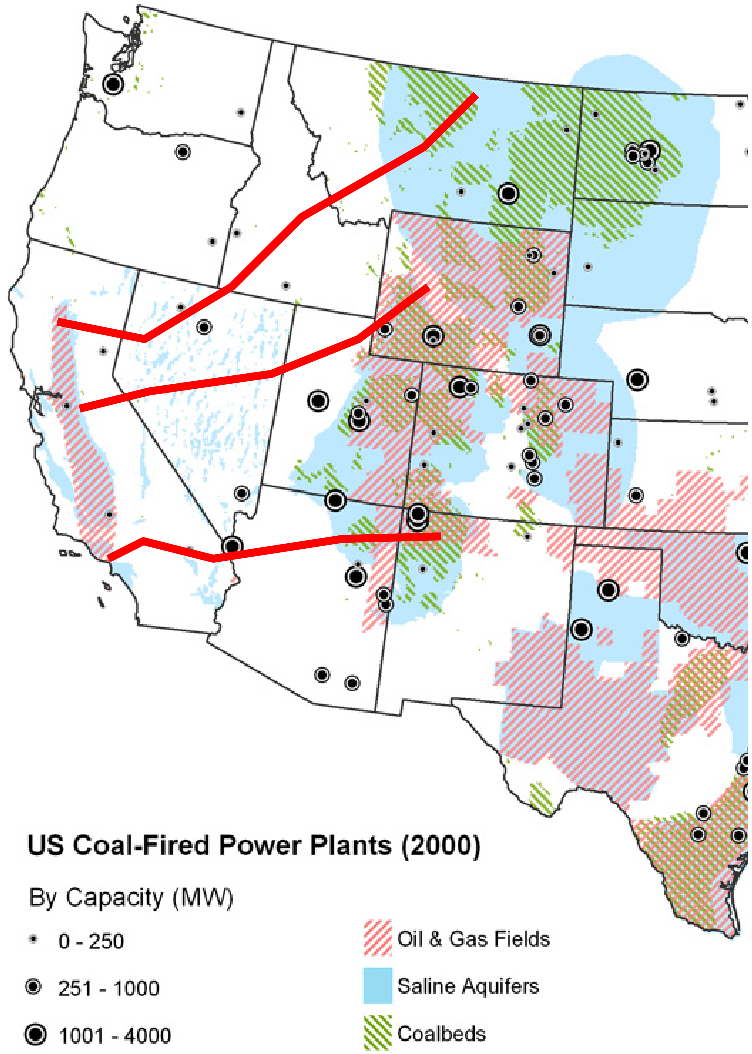
CA's SB1368 prohibits long-term power purchase agreements with emissions greater than natural gas plants: other states considering

CA's AB32 targets cannot be met with efficiency and renewable improvements alone

WGA's carbon markets initiative

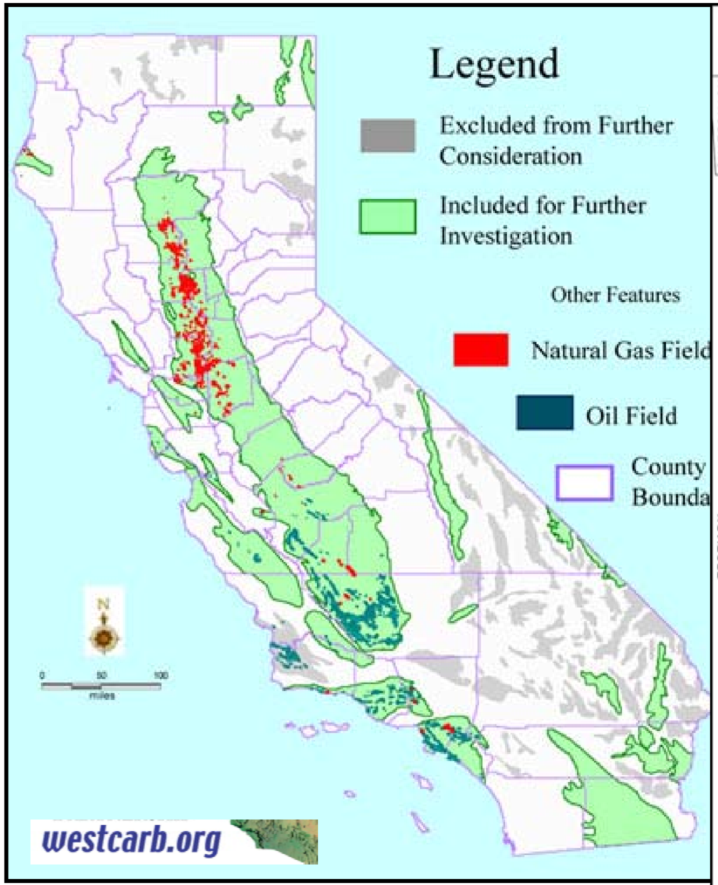
AB1925, New Mexico executive orders provides incentives for CCS deployment

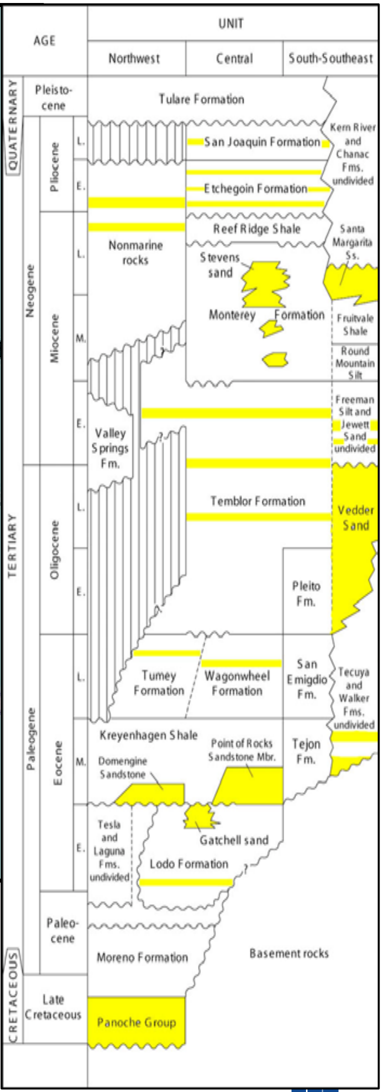
Actions pending in WY, MT, CO on CCS regulatory and legal framework



Preliminary estimates suggest California has an abundance of sequestration resource

- **Current WESTCARB estimates at 300 Gt capacity, mostly in Central Valley.**
- ***This is 10,000 times more than CA's point source emissions***
- **These estimates are preliminary, conservative and likely underestimates.**
- **Similar resource in WY, UT, NM, CO, MT each**





Site characterization is needed to turn resource into reserves

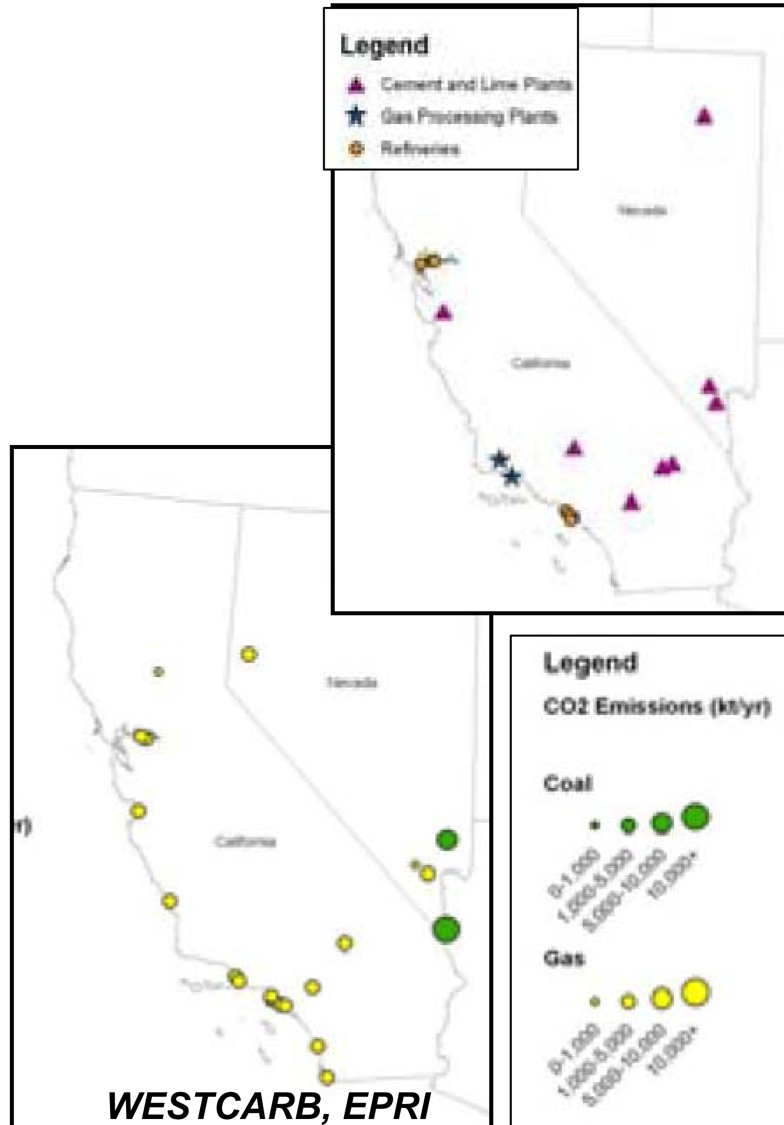
CCS opportunities in CA are large and could provide short- and long-term benefits

GlobalSecurity
Anticipate • Innovate • Deliver

Unique mix of sources attractive for state AB32 compliance

Four high-impact targets for CCS deployment *in state*

- Refineries
- Cement
- Zero-emission gas
- With biofuels

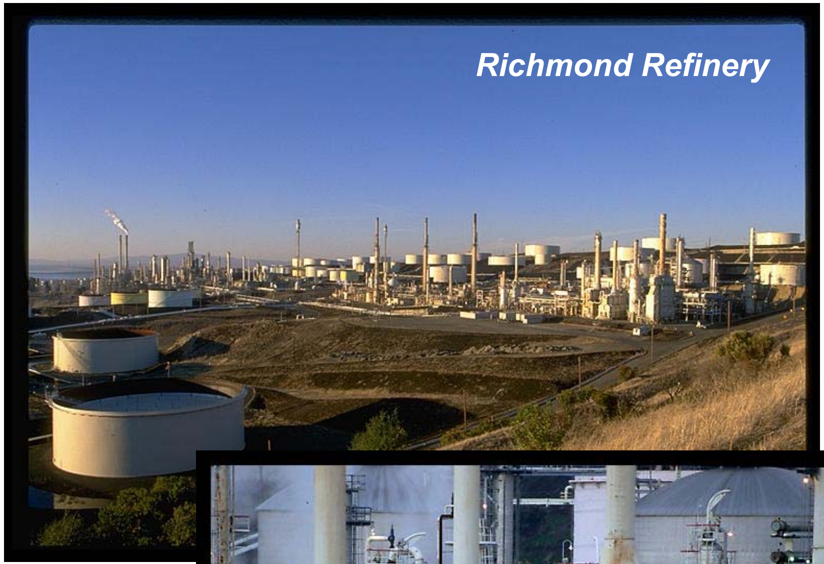


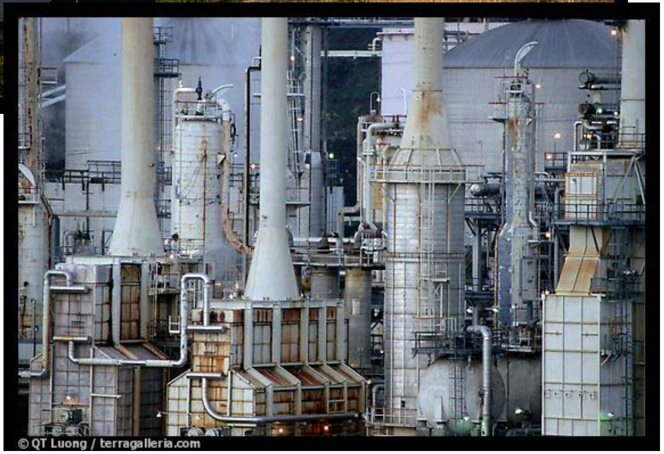
WESTCARB, EPRI

Refineries are a critical industry for the state with large emissions footprints

Both opportunities & problems

- Persistent large point sources for CO_2 and pollution
- Key industry for, CA fuel emission requirements, new low-carbon standards
- Cannot expand due to criteria pollution restrictions
- Importing fuels will “offshore” emissions





Could capture & sequester pure CO_2 streams

New technology for high carbon processes

CCS could both dramatically reduce refinery emissions and increase production

The cement industry represents ~3% of CA CO_2 emissions and a large industry

The cement making process creates CO_2

- Concern about offshoring cement manufacturers
- Importing cement = importing emissions too!

LLNL can help with special capabilities and experience

- Accelerated limestone weathering (AWL) technology
- Removes NO_x, SO_X with CO_2
- ICAT proposal w/ Davenport Cement

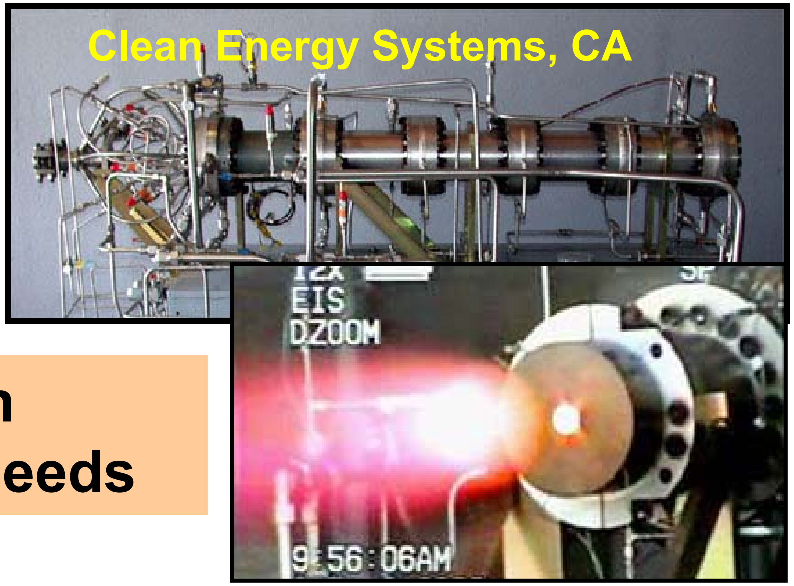
To get to AB32 limits, natural gas emissions must be reduced during demand growth

NG plants source 25 M t CO_2/y in CA

Likely to grow under SB1368

NGCC-CCS could create export industry in state & help balance renewable loads

Sequestration resource near many current plants and proposed new builds, especially within central valley



Currently not clear if post-combustion capture or oxyfiring is best for state needs

Biofuels + CCS create unusual opportunities for emissions reduction in CA

CCS could help conventional biomass plants in central valley

- *Negative* emission plant
- Combine with EOR to help economics
- Reduce current agricultural wastes

CCS could help emerging biofuels industries

- Reduce fuel carbon footprint (1/3:1/3:1/3)
- Help achieve low-carbon fuel standards

CCS could further improve emissions profile of biofuels in state

CCS in California: potential benefits, special considerations, strong skills

Mix of large, stationary CO_2 sources is unique

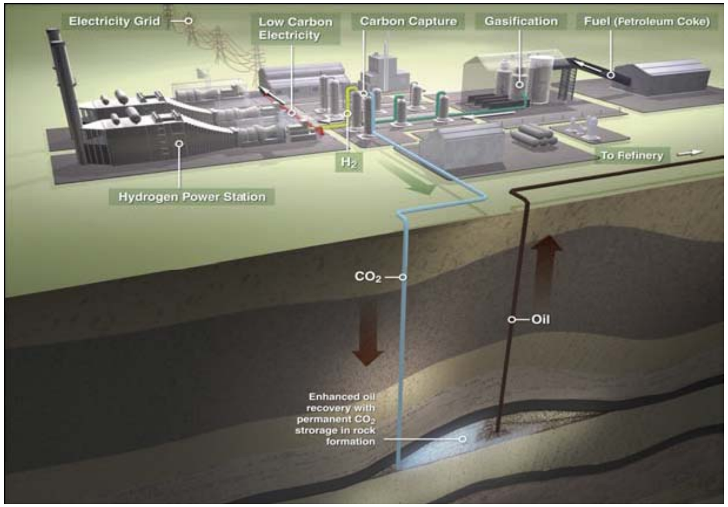
- Natural gas power plants: ~25 MM tons/y
- Refineries, gas processing, cement can provide low-cost opportunities: ~17 MM tons/y
- Coal-based electricity imported: CO_2 to be regulated by the CPUC
- Interest in biomass electric generation; possibility of “net negative” emissions

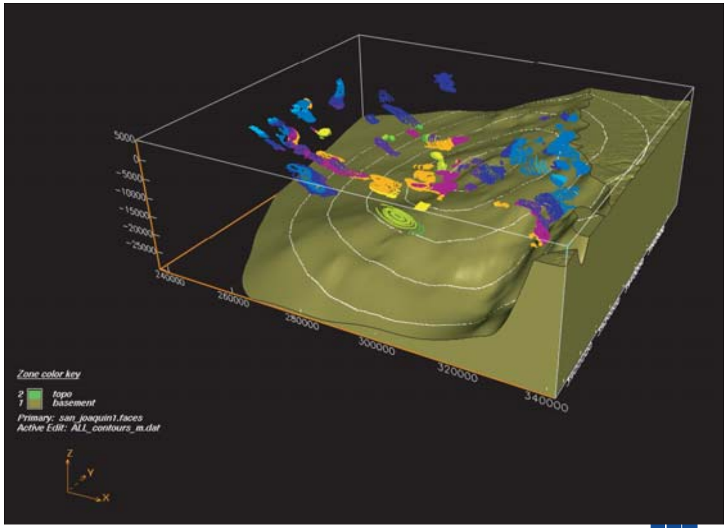
California has an excellent technical & physical infrastructure

- Agencies (CEC; WESTCARB; DOG)
- National Labs (LLNL and LBNL) +EPRI
- CO_2 Capture Engineering (e.g., Fluor, Bechtel/Nexant, SPA Pacific)
- Oil companies (e.g. Chevron, Occidental)
- Strong universities (UC, Stanford)
- Pipeline rights-of-way, O&M experience

LLNL can support and enable CCS deployment for California

- We have already made major contributions to CCS in the state
  - Executed capacity estimates and develop methodologies
  - Worked with the CEC under AB1925 for guidance document
  - Developed capacity and site assessment methodologies
  - Partnered with key industrial actors to develop technology & deployment (BP, Chevron)
- We expect to make major contributions to CCS in the state
  - Develop low-cost carbon capture and separation technology with industry
  - Perfect tools and methods to monitor and verify CO_2 underground
  - Identify key hazards to CCS deployment and tools to assess and avoid risks
  - Respond to requests of regulatory agencies (CARB, CalEPA, DOGGR)





Conclusions

Current knowledge strongly supports carbon sequestration as a successful technology to dramatically reduce CO_2 emissions.

Current science and technology gaps appear resolvable at scale

Site characterization, monitoring, and hazard assessment & management are keys to safe and successful deployment

California's specific mix of carbon sources and geology provide real, near term opportunities to dramatically reduce emissions with CCS

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Some basic considerations relevant to the nature and magnitude of CO_2-related risks

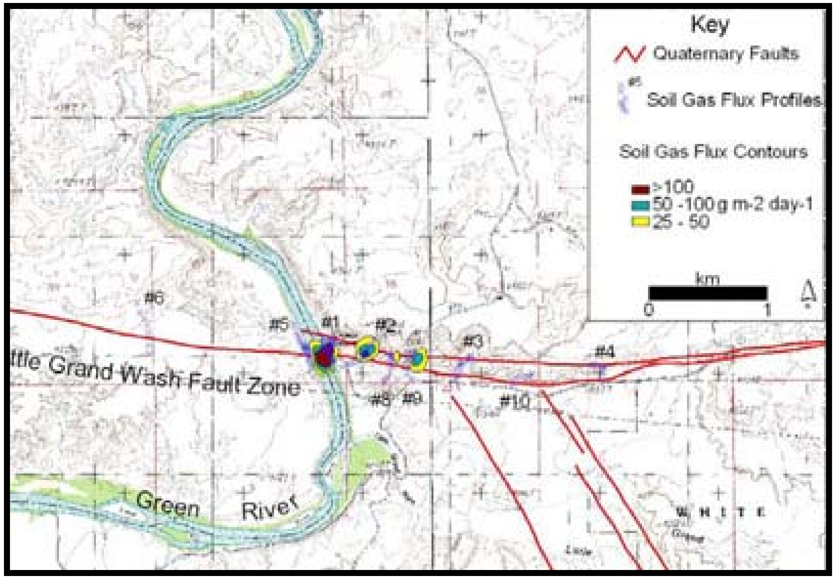
- CO_2 is not flammable or explosive
- CO_2 is not a dangerous gas except in very high concentrations (> 15,000 ppm)
  - Not to be confused with carbon monoxide (CO)
  - We inhale and exhale CO_2 with every breath
  - We drink carbonated (CO_2 containing) beverages
  - We buy "frozen" CO_2 for cooling (dry ice)
- We have successfully plugged and abandoned CO_2 injection wells, even badly damaged and failed wells
- Where human, animal or plant mortality has been attributable to CO_2 is due to volcanic releases in large quantities (e.g. Cameroon, Africa) or pooled in depressions or pits (Mammoth Mountain, California)

Little Grand Wash Fault soil surveys suggest fault leakage flux rates are extremely small

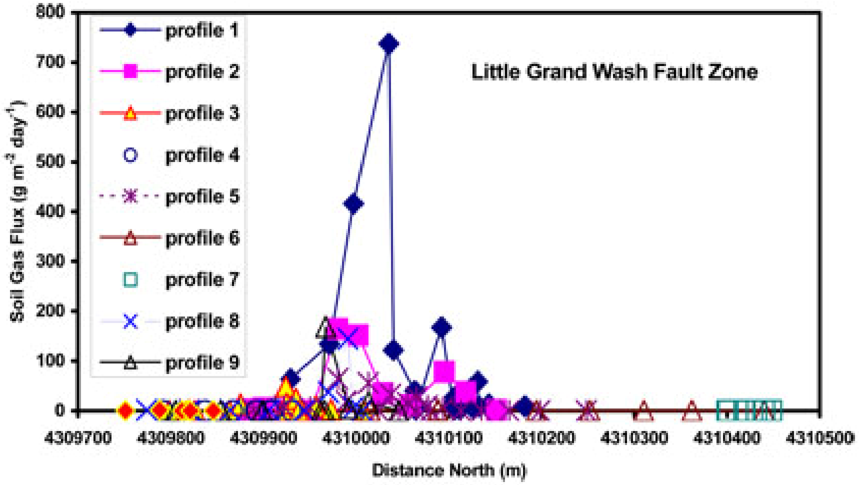
Allis et al. (2005) measured soil flux along the LGW fault zone.

Overall, concentrations were <0.1 kg/m²/d.

Integrated over the fault length and area, this is unlikely approach 1 ton/day.



At Crystal Geyser, it is highly likely that all fault-zone leakage is at least two orders of magnitude less than the well. This may be too small to detect with many surface monitoring approaches



Allis et al., 2005

Simulations of the largest hypothetical event suggest leakage appears to be manageable

GlobalSecurity
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Max. CO_2 flow rate:
7" inside diameter well

Depth (ft)	Flow rate (kg/s)	Flow rate (ton/day)
5036	225	1944
4614	217	1875
5102	226	1952
4882	224	1935

~2x Sheep Mt. event
~50x Crystal Geyser

Simulated hypothet
Max. flow rate even
Great plains: no wi

Simulated hypothetical
Max. flow rate event
Great plains: average wind

Acute (Short-Term) Effects

	Description	(ppm) Extent Area	Population Fatalities Casualties
	>TEEL-3: Death or irreversible health effects possible.	>40,000 71.5 m 6,840 m2	0 N/A N/A
	>TEEL-2 and TEEL-1: Serious health effects or impaired ability to take protective action.	>30,000 87.3 m 9,515 m2	0 N/A N/A

Note: Areas and counts in the table are cumulative. Casualties include both Fatal and Non-Fatal effects.

The HSE consequences from catastrophic well failure do not appear to present an undue or unmanageable risk.